

Node-Pair Selection Strategies for Traffic-Engineering Links in Link-Weight Design Based on Preventive Start-Time Optimization

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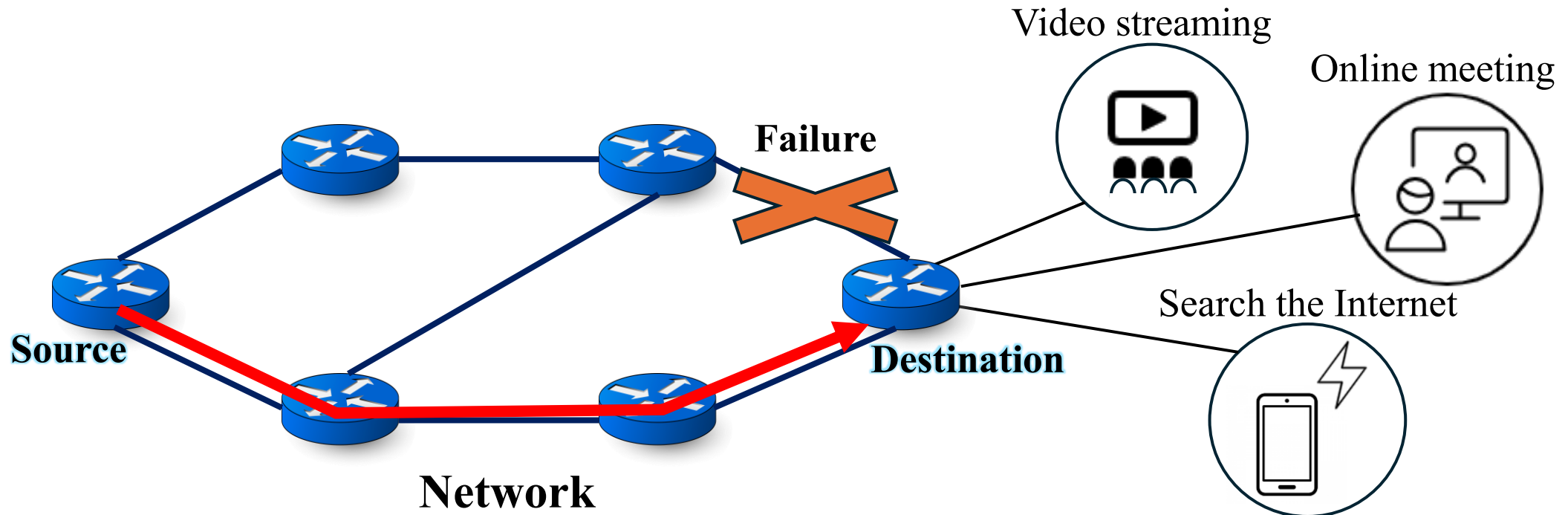
Outline

- Background
- Previous work
- Problem statement
- Node-pair selection strategies
- Performance evaluation
- Conclusion

Background: IP network

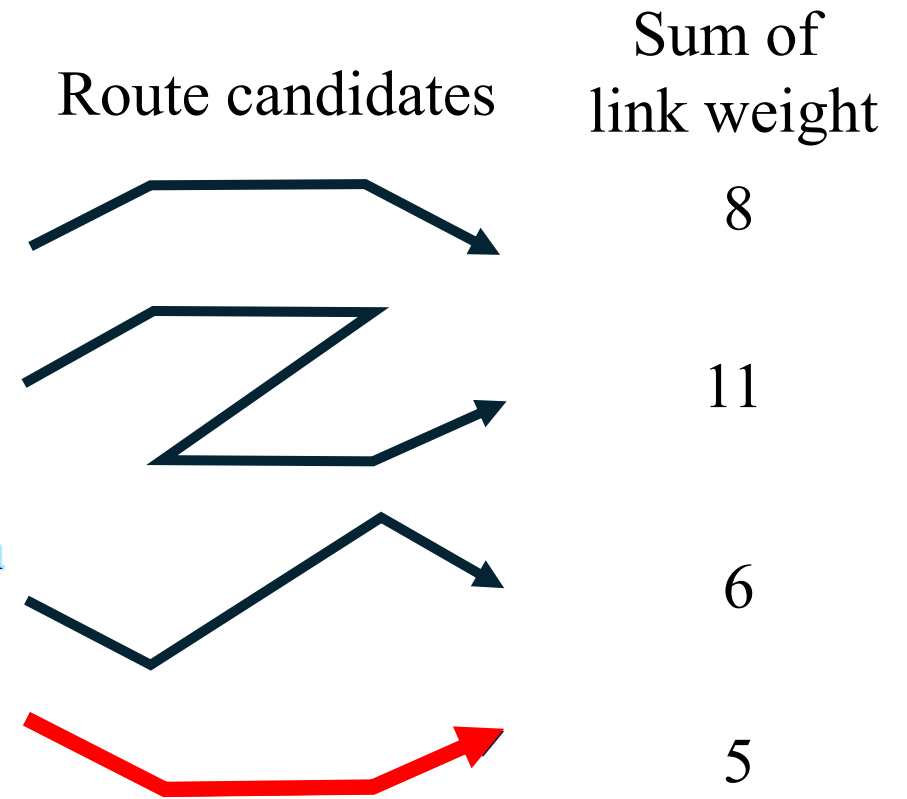
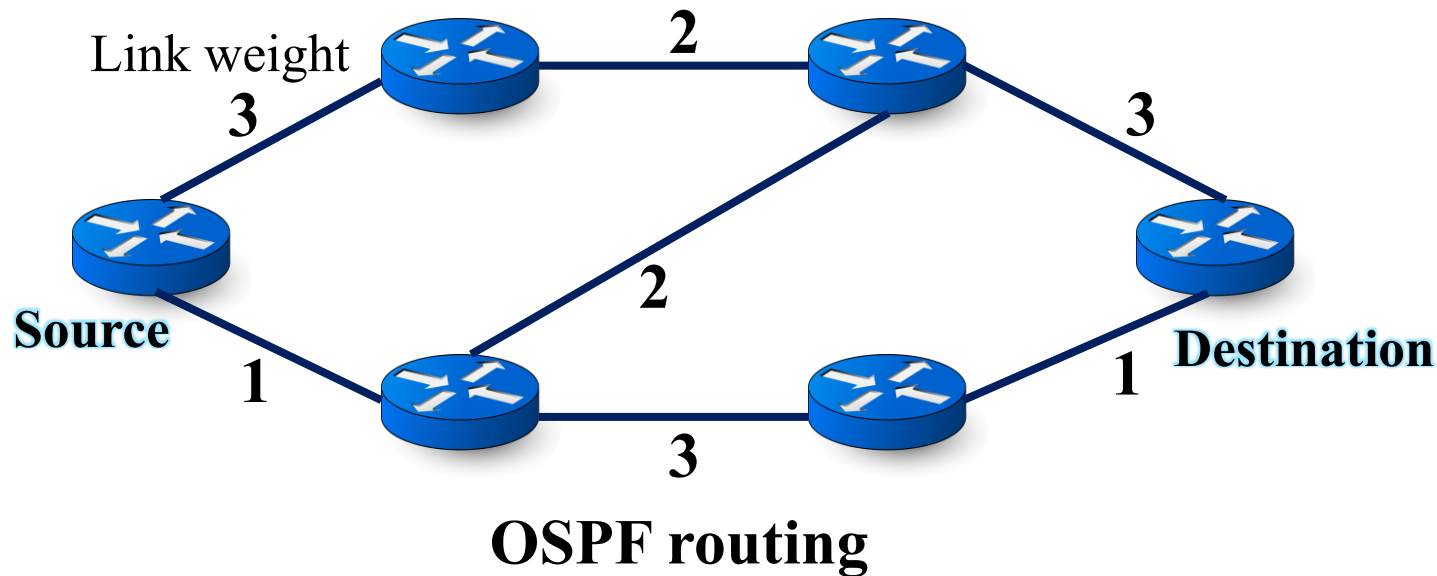
- Communication has become indispensable to daily life.
- Continuous service provision is required **even during network failures**.
- **Congestion must be reduced** as it increases delays of Real-time communication.
- Network operators wish to avoid adding physical resources or changing protocols.

IP: Internet protocol



Background: Open shortest path first (OSPF)

- OSPF: Select routes minimizing sum of link weights.
- Determining link weights \approx Determining a route [Fortz, IEEE, 2002].
- **Determining optimal link weights is NP-hard.**



[RFC 2328] J. Moy, "OSPF version 2," RFC 2328, Apr. 1998.

[Fortz, IEEE, 2002] B. Fortz and M. Thorup, "Optimizing OSPF/IS-IS weights in a changing world,"

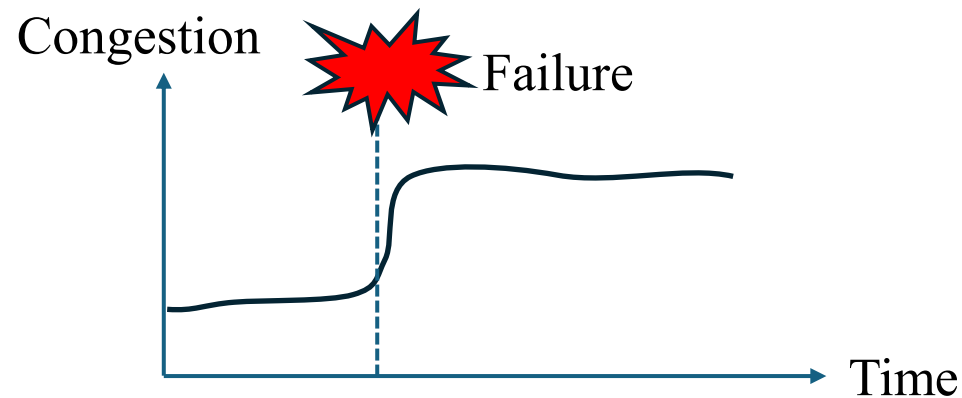
IEEE J. Sel. Areas Commun., vol. 20, no. 4, pp. 756–767, 2002.

Background: How to set link weights

Start-time optimization (SO)

Sets link weights at the beginning of network operation without considering link failure.

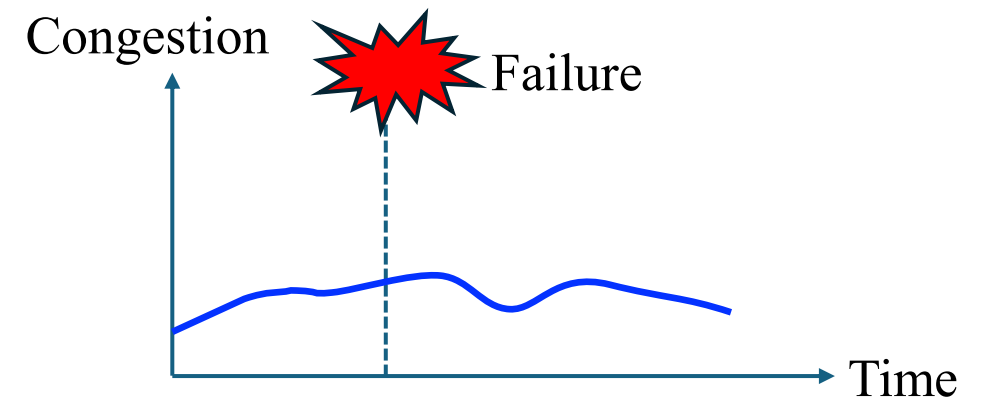
- Pros
 - Simple and computationally efficient.
- Cons
 - **Becomes suboptimal during link failures**, leading to potential congestion.



Preventive start-time optimization (PSO)

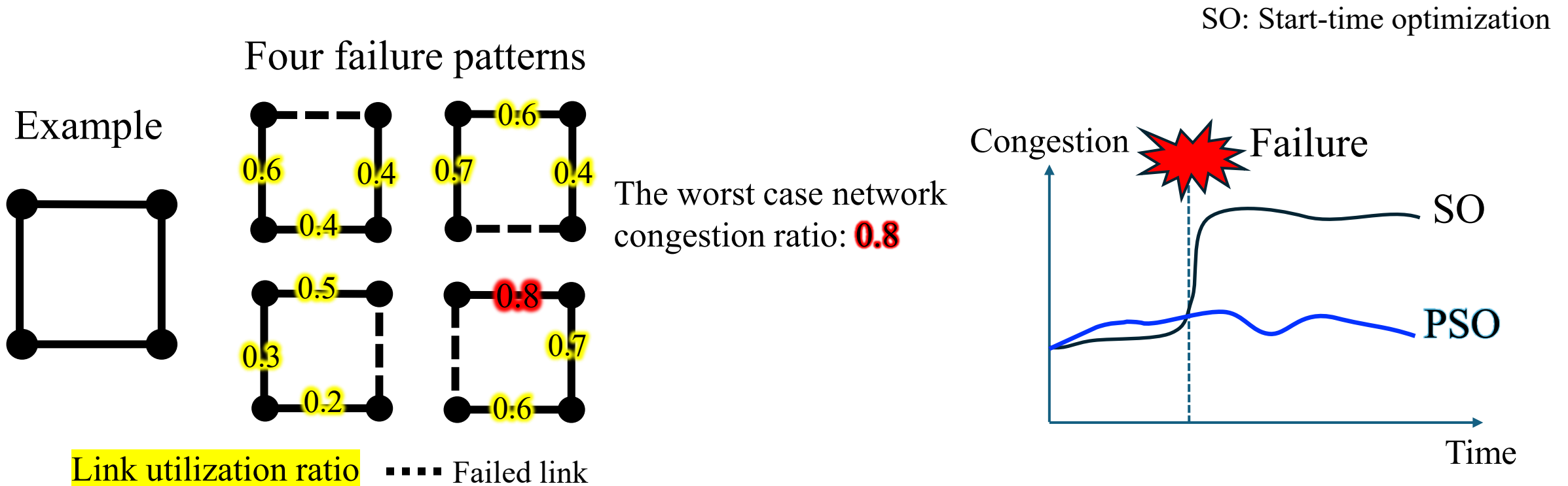
Sets link weights at the beginning of network operation **considering link failure**.

- Pros
 - **Reduce congestion under link failures.**
- Cons
 - Wasted effort when there are no link failures.



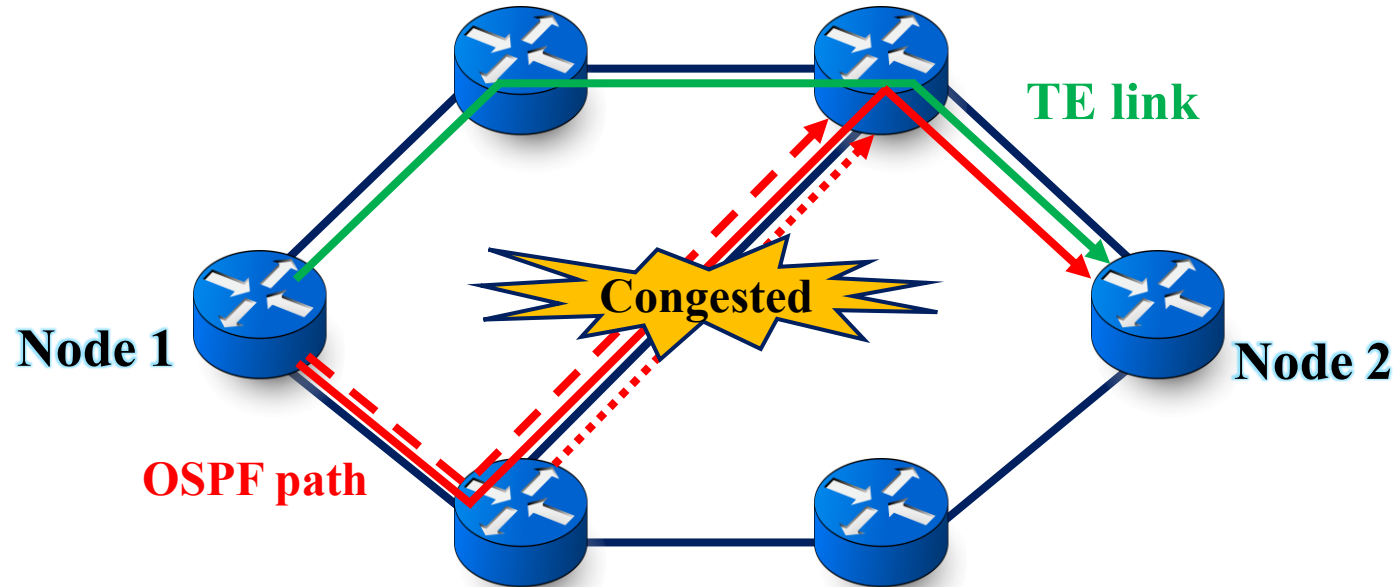
Background: Preventive start-time optimization (PSO)

- Sets link weights **at the beginning of network operation considering link failure** [Kamrul, 2010].
- Minimize the worst-case congestion among link failures.



Background: Traffic engineering (TE) link

- TE links connect logically non-adjacent nodes using the resources of physical links.
- TE links increase route flexibility.
- Reducing network congestion and improving overall network resource utilization.



TE link to avoid congestion

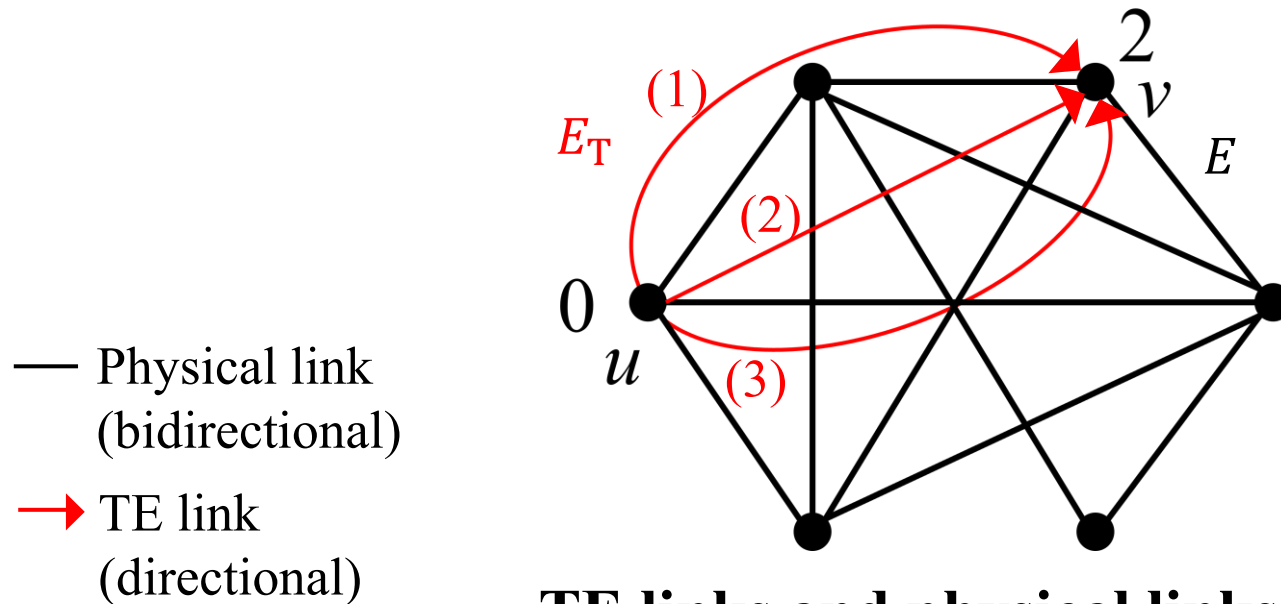
OSPF: Open shortest path first

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Previous work: PSO-TE

- **Link-weight design model with TE links based on PSO** [Nakashima, IEEE ICNC, 2025]
 - Create topology including TE links and physical links.
 - Determine weights of TE links and physical links by PSO.



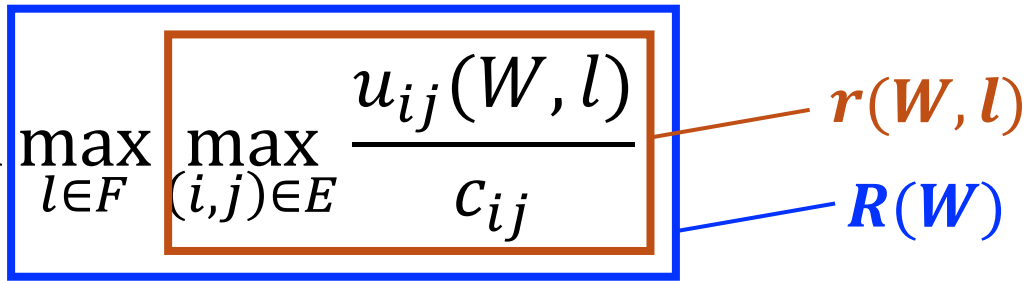
PSO: Preventive start-time optimization
TE: Traffic engineering

E : Set of physical links
 V : Set of nodes
 E_T : Set of TE links
 E' : Set of all links

TE links and physical links
 $G(V, E'), E' = E \cup E_T$

Previous work: Formulation

- Formulate PSO-TE as a mathematical optimization problem. PSO: Preventive start-time optimization
TE: Traffic engineering
- Objective: **Minimize the worst-case network congestion ratio among all failure scenarios.**

$$W_{\text{PSO-TE}} = \arg \min_W \max_{l \in F} \max_{(i,j) \in E} \frac{u_{ij}(W, l)}{c_{ij}}$$


Notations	Descriptions
W	Set of link weights
$u_{ij}(W, l)$	Total traffic volume passing through of link $(i, j) \in E$
c_{ij}	Capacity of $(i, j) \in E$
$r(W, l)$	Maximum link utilization ratio $(u_{ij}(W, l) / c_{ij})$ among all links $(i, j) \in E$
$R(W)$	Worst-case network congestion ratio among all link failure scenarios $l \in F$

Previous work: Motivating example

- Step 1: The **non-adjacent** node pairs with the **m largest traffic demands.**

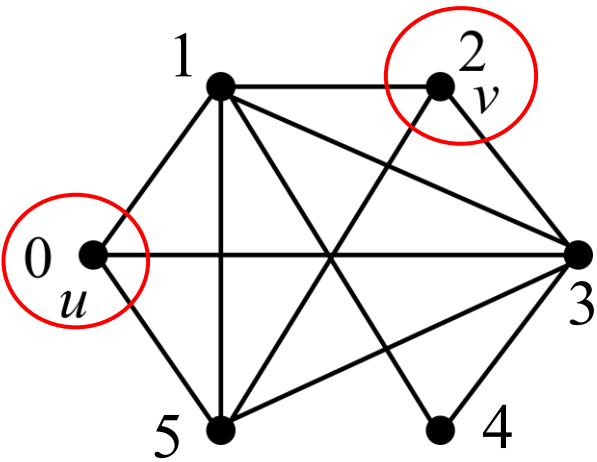
- Select $m = 1$ node pair of $(u, v) = (0, 2)$.

TE: Traffic engineering

- Step 2: **At most k paths with the smallest number of hops** in each node pair.

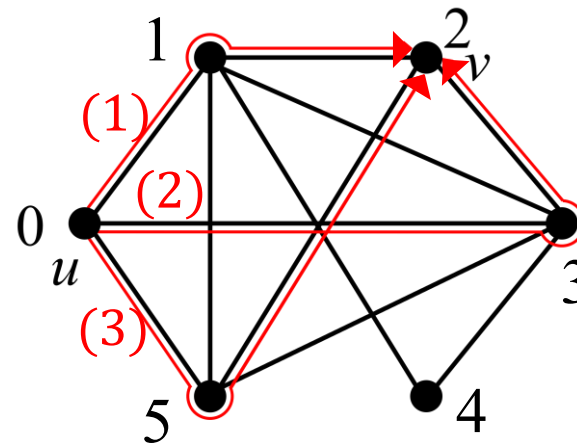
- Select $k = 3$ paths in node pair $(u, v) = (0, 2)$.

Select node pairs



Node pair	Traffic demand
0→1	45
1→0	20
0→2	43
2→0	34
...	...
5→4	35
4→5	42

Select paths



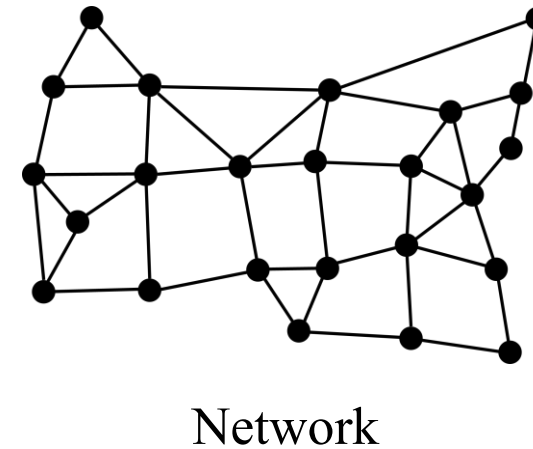
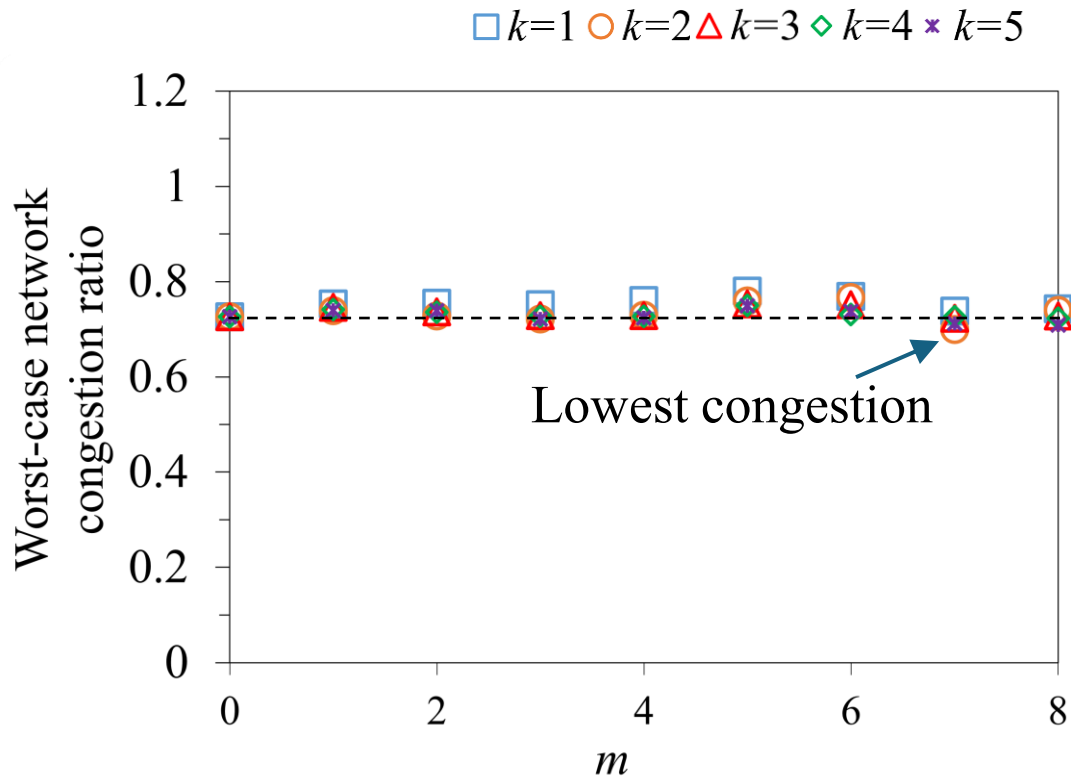
— Physical link (bidirectional)
 → TE link (directional)

Type	Link	weight
physical link	0→1	1
	1→0	3
	2→5	4
	5→2	1

TE link	0→2 (1)	2
	0→2 (2)	5
	0→2 (3)	1

Previous work: Worst-case network congestion ratio

- By appropriately setting m and k , the worst-case congestion ratio can be reduced.
- Including TE links **reduces the network congestion ratio by 3.7%**.



TE: Traffic engineering

m : Number of node pairs setting TE links

k : Number of paths in each node pair of TE links

Problem statement

- Previous work:
 - Previous study incorporates **TE links** into PSO.
 - TE links are set up between node pairs in traffic-demand descending order.
 - It does not investigate alternative node-pair selection strategies for TE link setup.
 - It **may not be the most effective strategy** for setting up TE links.
- A question arises:
 - *Do the differences in node-pair selection strategies affect the performance of PSO-TE?*

PSO: Preventive start-time optimization

TE: Traffic engineering

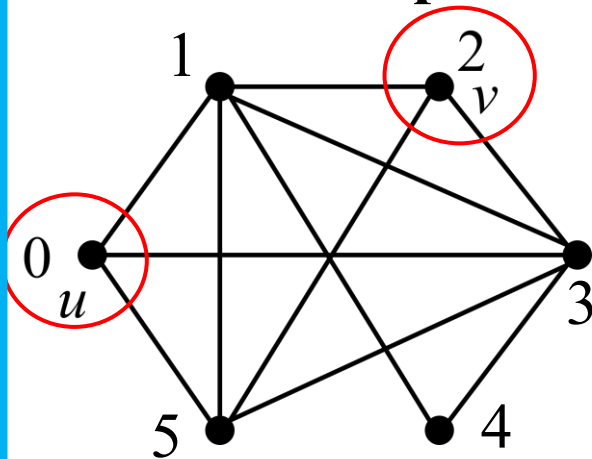
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- **Node-pair selection strategies**
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Node-pair selection strategies

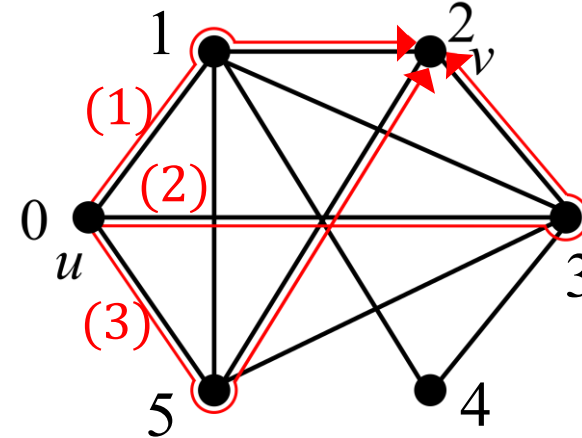
- Step 1: The **non-adjacent** node pairs with the **m largest traffic demands**.
 - Select $m = 1$ node pair of $(u, v) = (0, 2)$.
- Step 2: **At most k paths with the smallest number of hops** in each node pair.
 - Select $k = 3$ paths in node pair $(u, v) = (0, 2)$.

Select node pairs



Node pair	Traffic demand
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Select paths



— Physical link (bidirectional)
 → TE link (directional)

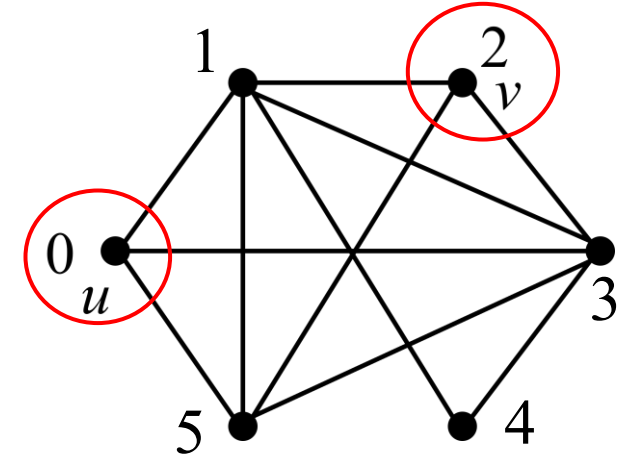
TE: Traffic engineering

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	2→5	4
	5→2	1

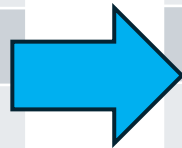
TE link	0→2 (1)	2
	0→2 (2)	5
	0→2 (3)	1

Node-pair selection strategies

- We define six node-pair selection strategies:
 - traffic-demand descending (TD)
 - traffic-demand ascending (TA)
 - hop-count descending and traffic-demand descending (HDTD)
 - hop-count descending and traffic-demand ascending (HDTA)
 - hop-count ascending and traffic-demand descending (HATD)
 - hop-count ascending and traffic-demand ascending (HATA)



Node pair	Hop count	Traffic demand
0→1	1	45
1→0	1	20
0→2	2	43
2→0	2	34
...
5→4	2	35
4→5	2	42



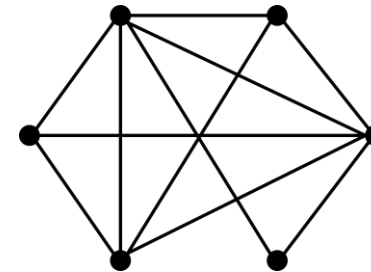
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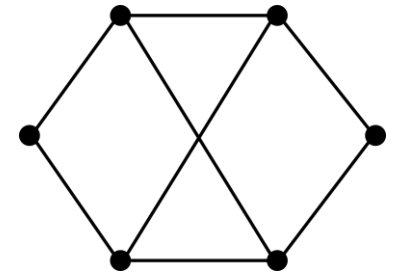
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Performance evaluation: Experiment setup

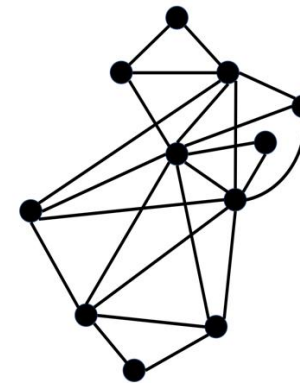
- Examined networks:
 - Four networks
- Link capacity:
 - Uniform distribution in the range of $(10U_C, 100U_C)$.
 - U_C is a given constant positive value.
- Traffic demand:
 - Uniform distribution in the range of $(0, 100U_D)$.
 - U_D is a given constant positive value.
- Parameters of TE links:
 - m in the range of $(0, 8)$. ($m = 0$ means no TE link)
 - k in the range of $(1, 5)$.



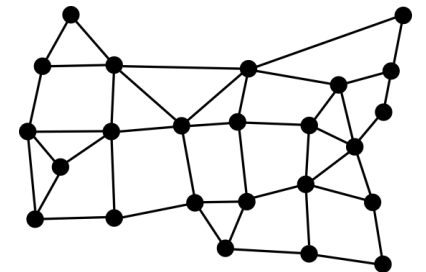
Network (a)



Network (b)



Network (c)



Network (d)

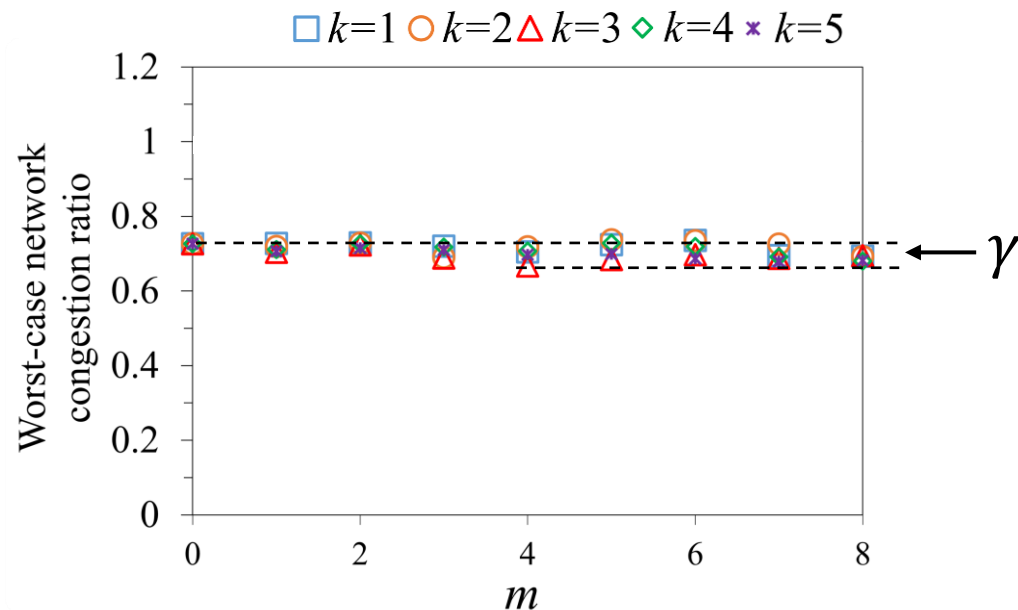
m : Number of node pairs setting TE links

k : Number of paths in each node pair of TE links

Performance evaluation: Congestion reduction by TE links

- γ shows the reduction of the network congestion ratio by adding TE links.

Congestion ratio of the network (d)



Worst congestion ratio with $(m, k) = (m', k')$, which are the values of m and k that achieve the best reduction in the network congestion ratio.

$$\gamma = \frac{r(0,0) - r(m',k')}{r(0,0)}$$

Worst-case congestion ratio with $(m, k) = (0, 0)$.

TE: Traffic engineering

m : Number of node pairs setting TE links

k : Number of paths in each node pair of TE links

Performance evaluation: Node-pair selection strategies

- The greatest difference in the reduction observed is **6.7%**. In that network, the best-performing strategy achieves 8.2%, whereas the worst achieves 1.5%.
- Employing a suitable node-pair selection strategy for setting up TE links is effective **in a large network**.

Congestion reduction ratio γ of six strategies

Strategy	Network (a)	Network (b)	Network (c)	Network (d)	Average
TD	0.0006	0.027	0.0086	0.037	0.018
TA	0.0004	0.023	0.0093	0.021	0.013
HDTD	0.0006	0.028	0.0090	0.082	0.030
HDTA	0.0004	0.017	0.0094	0.051	0.020
HATD	0.0006	0.027	0.0083	0.021	0.014
HATA	0.0004	0.025	0.0080	0.015	0.012

TD: traffic-demand descending TA: traffic-demand ascending
HDTD: hop-count descending and traffic-demand descending
HDTA: hop-count descending and traffic-demand ascending
HATD: hop-count ascending and traffic-demand descending
HATA: hop-count ascending and traffic-demand ascending

Performance evaluation: Node-pair selection strategies

- **HDTD has the largest average reduction ratio.**
 - TE links between node pairs with larger hop counts can enhance route flexibility.
 - TE links between node pairs with higher traffic demand can affect a larger amount of traffic in the network.

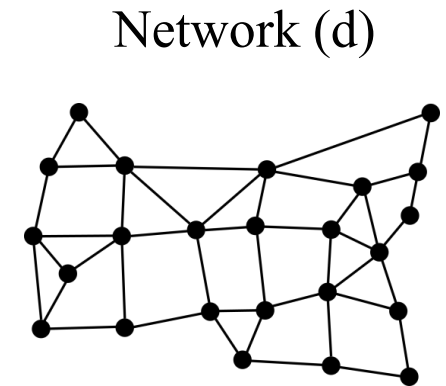
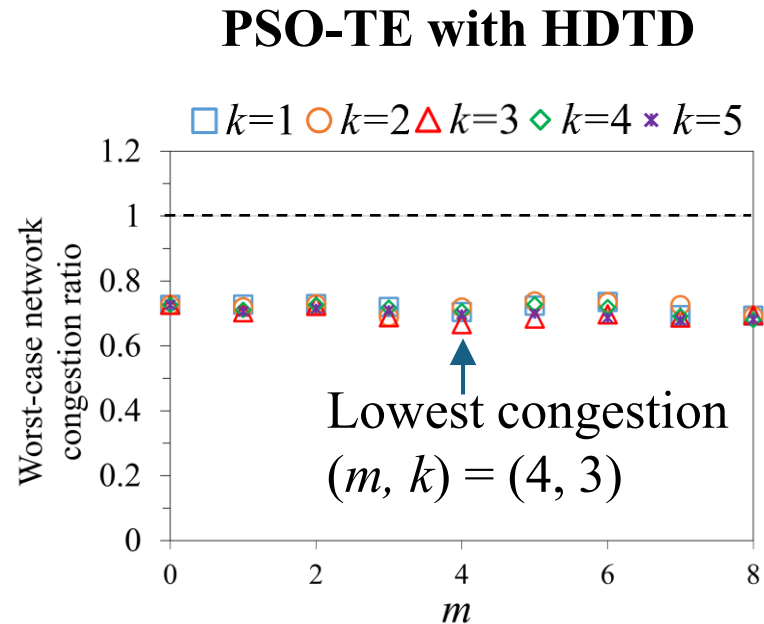
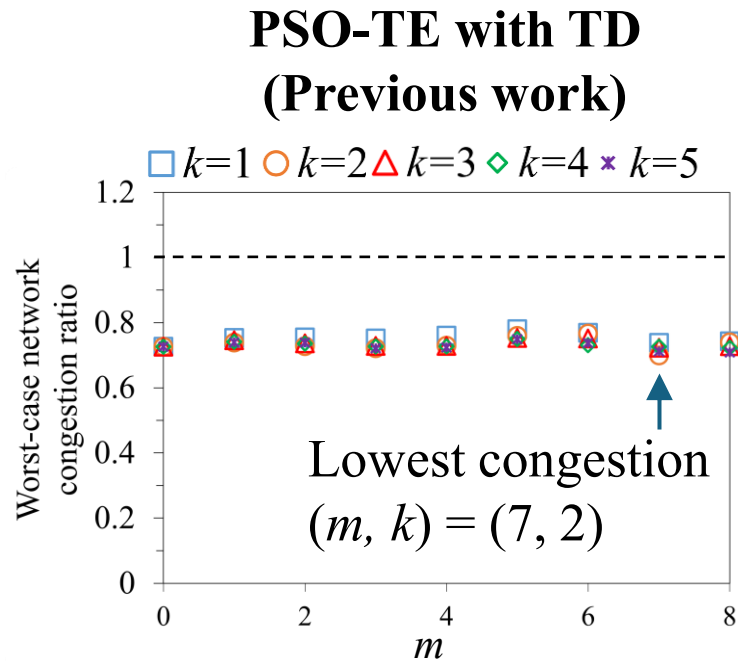
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TD: traffic-demand descending TA: traffic-demand ascending
HDTD: hop-count descending and traffic-demand descending
HDTA: hop-count descending and traffic-demand ascending
HATD: hop-count ascending and traffic-demand descending
HATA: hop-count ascending and traffic-demand ascending

Performance evaluation: Reduction of the lowest congestion

- HDTD reduces the lowest congestion ratio by 4.5% compared to TD.



m : Number of node pairs setting TE links

k : Number of paths in each node pair of TE links

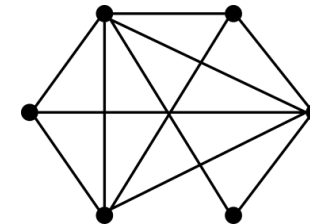
TD: traffic-demand descending HDTD: hop-count descending and traffic-demand descending

PSO: Preventive start-time optimization TE: Traffic engineering

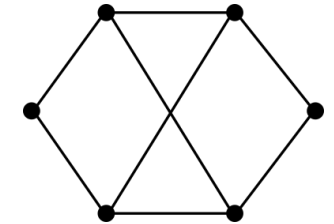
Performance evaluation: Computation time of PSO-TE with HDTD

- The computation time increases as the number of TE links and the network size increase.
- The more TE links and the larger the network, **the larger the solution space becomes.**

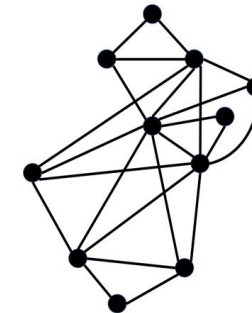
Network type	(m, k)	Time [s]
Network (a)	(0, 0)	2.8
	(3, 4)	7.2
Network (b)	(0, 0)	5.9
	(5, 4)	13
Network (c)	(0, 0)	46
	(7, 5)	396
Network (d)	(0, 0)	504
	(4, 3)	2042



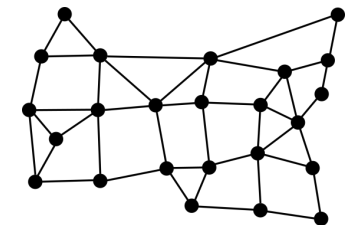
Network (a)



Network (b)



Network (c)



Network (d)

m : Number of node pairs setting TE links

k : Number of paths in each node pair of TE links

HDTD: hop-count descending and traffic-demand descending

PSO: Preventive start-time optimization TE: Traffic engineering

Conclusion

- We investigated node-pair selection strategies for the link-weight design model based on preventive start-time optimization with TE links (PSO-TE).
- Numerical results showed that the differences in **node-pair selection strategies have a significant impact on the performance of PSO-TE**.
 - TE links between node pairs with larger hop counts enhance route flexibility.
 - TE links between node pairs with higher traffic demand influence a larger amount of traffic in the network.
 - Employing a suitable node-pair selection strategy for setting up TE links is effective in a large network.

PSO: Preventive start-time optimization
TE: Traffic engineering